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The Relooping Fashion Initiative

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Published: 01/01/2018

Document Version
Publisher's final version

[Link to publication](#)

Please cite the original version:

Heikkilä, P. (Ed.), Fontell, P., Kamppuri, T., Mensonen, A., Määttänen, M., Pitkänen, M., Raudaskoski, A., Vehmas, K., Vehviläinen, M., & Harlin, A. (2018). *The Relooping Fashion Initiative*. VTT Technical Research Centre of Finland. VTT Research Report No. VTT-R-01703-18

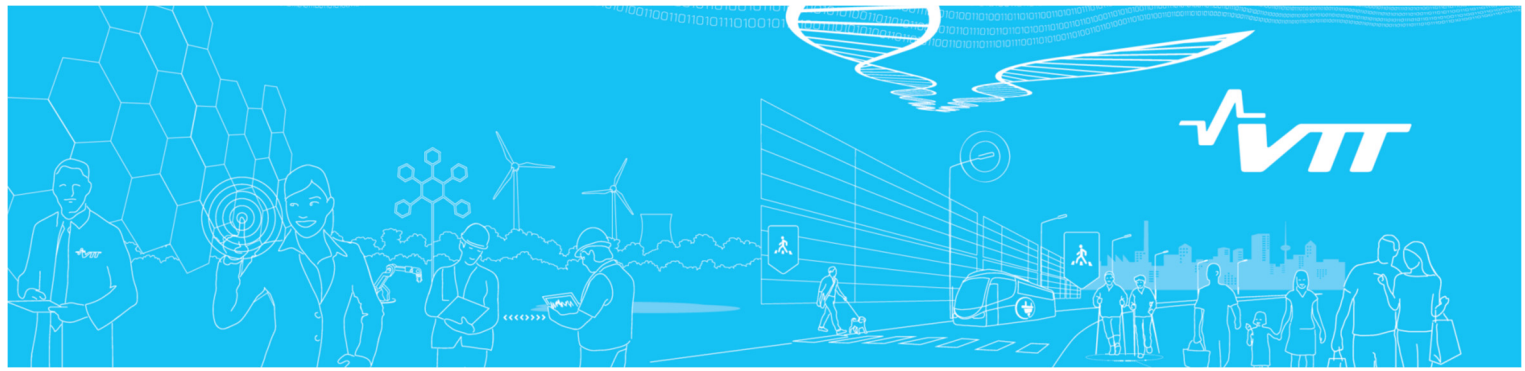


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RESEARCH REPORT

VTT-R-01703-18



The Relooping Fashion Initiative

Authors: Pirjo Heikkilä (ed.), Paula Fontell, Taina Kamppuri, Aino Mensonen, Marjo Määttänen, Marja Pitkänen, Anne Raudaskoski, Kaisa Vehmas, Marianna Vehviläinen, Ali Harlin

Confidentiality: Public / Annexes Confidential

Report's title The Relooping Fashion Initiative								
Customers Tekes, Ethica, Pääkaupunkiseudun kierrätyskeskus, Seppälä, RePack, Remeo, Pure Waste Textiles, Lindström, Touchpoint	Order references 1325/31/2015 923/31/2016							
Project name Circular Economy of Textiles / Tekstiilien suljettu kiertotalous	Project number/Short name 105881 / TEKI							
Author(s) Pirjo Heikkilä (ed.), Paula Fontell, Taina Kamppuri, Aino Mensonen, Marjo Määttänen, Marja Pitkänen, Anne Raudaskoski, Kaisa Vehmas, Marianna Vehviläinen, Ali Harlin	Pages 73							
Keywords textile recycling, circular ecosystem, closed loop, chemical recycling, cotton, cellulose carbamate, ecological fibres	Report identification code VTT-R-01703-18							
Summary <p>Circular Economy of Textiles (TEKI) –project, also known as The Relooping Fashion Initiative, aimed for piloting and modelling the closed circular ecosystem for textiles. Such ecosystem would lay a foundation for utilization of textiles in a new way. Aim was to produce business opportunities and shared value for all parties within value chain.</p> <p>Our consortium included actors from all stages of the value chain to enable practical implementation of post-consumer textile recycling pilot. Prototype materials - fibres, yarns, and knitted materials and products - were obtained from lab and pilot scale trials, and overall feasibility of the chemical recycling for post-consumer cotton was evaluated. However, the part closing the loop in the pilot, a retail collection, was not realised yet. Modelling of ecosystem produced description of actors, processes and material flow within closed textile recycling ecosystem as well as description of division of added value within ecosystem. We also studied consumer habits and consumer communication as method for committing consumers to circular economy.</p> <p>Main outcomes of the project were: 1) successful industrial scale pilot taking VTT's cellulose carbamate technology as chemical recycling route for cotton materials into commercialization bath; 2) gaining better understanding of missing pieces of circular business ecosystem for textiles and launching activities to fill in the value network; and 3) increased consumer awareness through better understanding on consumer communication, which can increase the awareness about possibilities and need for textile recycling in society in general.</p>								
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Tampere 31.5.2018 <table border="0"> <tr> <td>Edited by</td> <td>Reviewed by</td> <td>Accepted by</td> </tr> <tr> <td>Pirjo Heikkilä, Senior Scientist</td> <td>Ali Harlin, Research Professor</td> <td>Jani Lehto, Vice President</td> </tr> </table>			Edited by	Reviewed by	Accepted by	Pirjo Heikkilä, Senior Scientist	Ali Harlin, Research Professor	Jani Lehto, Vice President
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Distribution (customer and VTT) Tekes, VTT, Ethica, Pääkaupunkiseudun kierrätyskeskus, RePack, Remeo, Pure Waste Textiles, Lindström, Touchpoint								
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Preface

This report summarizes work carried out in Tekstiilien suljettu kiertotalous / Circular Economy of Textiles (TEKI) –project 5/2015-12/2017 (1325/31/2015 and 923/31/2016). Work was supported by Tekes – the Finnish Funding Agency for Innovation as part of Tekes’ Green Growth program. Project consortium included four companies - Ethica, Helsinki Metropolitan Area Reuse Centre, Seppälä and RePack - who had own Tekes-funded projects; two companies - Pure Waste Textiles and Remeo (formerly SUEZ / SITA) - who participated piloting and project with their own resources without external funding; and two companies - Touchpoint and Lindström - who provided funding for the pilot (923/31/2016).

The overall goal of the project was to for pilot and model the closed circular ecosystem for textiles. Pilot work and technology evaluation related to recycling of discarded cotton textiles using on cellulose carbamate (CCA) technology, while modelling work was carried out in wider scope, including whole clothing and interior textile sector, as well as other loops of circular economy models. Consumers who have major role in circular economy of textiles were addressed within consumer study.

Responsible leader of the project was Research Professor Ali Harlin and project manager was Senior Scientist Pirjo Heikkilä. Key personnel of the project at VTT also included Senior Scientists Marjo Määttänen, Marianna Vehviläinen, Marja Pitkänen, Aino Mensonen and Kaisa Vehmas. Large group of other researchers as well as technical staff participated for the project work.

Members of the steering group and key personnel from participating companies within duration of the project also included Paula Fontell and Anne Raudaskoski (Ethica); Pia Engström, Hanna Lilja and Touvi Kurttio (The Helsinki Metropolitan Area Reuse Centre); Petri Piirainen and Jonne Hellgren (RePack); Erica Adlercreutz, Kati Kivimäki, Arja Paakkola-Saarinen, Maria Hentilä, and Eveliina Melentjeff (Seppälä); Christian Hinderesson, Tiila Korhonen and Janne Vehmaa (Remeo/SUEZ/SITA); Jukka Pesola, Anders Bengs and Noora Alhainen (Pure Waste Textiles); Outi Luukko, Carita Peltonen and Arja Paakkola-Saarinen (Touchpoint); and Seija Forss, Sini Rajala and Tarja Hämäläinen (Lindström). Our contact persons in Tekes were Senior Advisers Erja Ämmälähti and Tuomas Lehtinen.

The project had an advisory board to mirror the needs of different interest groups. This group included representatives of SYKE, SITRA, researchers from various universities, as well as companies and organization involved in textile recycling.

Authors would like to also acknowledge students participated into evaluation of techno-economical feasibility and environmental aspects of CCA recycling technology: Leena Katajainen (University of Jyväskylä); and Aki Henttonen, Reetta Hassinen, Iiro Perttula, and Henri Harlin (Aalto University)

Tampere 31.5.2018

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Abbreviations

CCA	Cellulose carbamate
CO	Cotton
dtex	decitex, unit of linear density of fibres = mass in grams per 10 000 m
GWP	Global Warming Potential
HMARC	Helsinki Metropolitan Area Reuse Centre
IFC	Infinite Fibre Company, VTT spin-off developing CCA technology further
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
NIR	Near Infra Red
PES	Polyester
PET	Polyethylene terephthalate – one type of polyester
PTA	Purified terephthalic acid
RQ	Research question
TEKI	Acronym of the project
tex	unit of linear mass density of fibre/yarns = mass in grams per 1 000 m
TRL	Technology Readiness Level
WP	Workpackage

1. Introduction

Textile and clothing industry is one of the largest consumer goods industry sector in the world. Annual use of textile fibres surpassed 100 million tonnes in 2016 (The Fiber Year, 2017) and it is expected to grow few percent's annually. Share of the man-made fibres now is approximately 70 % of the global market. Increasing textile fibre production to correspond to increasing demand cannot be done sustainably with existing textile fibre basis. Synthetic fibres, like polyester (PES) - the most used one, are oil based and thus, coming from non-renewable resource and are increasing global problem caused by micro plastics. Cotton, which is the most used natural fibre and thus renewable, is on the other hand using a lot of water for cultivation. Additional sustainability issues of cotton include use of land, which might be needed for cultivation of food plants, as well as high used on fertilizers and pesticides. Furthermore, fashion is second most polluting industries in the world after oil industry, it uses 25 % of all chemical produced world-wide, and is number two polluter of clean water after agriculture (SITRA, 2015).

Utilization of recycled textile as a raw material source is an under-utilized raw material source: share of recycled materials is marginal. Increased recycling of textile materials would also reduce the amount of municipal waste, which is in accordance with current requirements of European Commission (2017). Textile used per capita in Finland is more than 13 kg per capita per year, and it has been evaluated in 2012 that at least 70 million kg of textiles was discarded annual (Dahlbo *et al.*, 2015). Only one fifth of this material was collected and sorted and almost all of the non-collected material remained within mixed waste, thus, would be currently burned into energy. Amount of textile waste currently generated in Finland can expected to be around 90 million kg, while percentages of collected and re-utilised fractions are probably not changed much yet. Increased re-use and especially recycling of non-reusable materials within mechanical, thermal and chemical routes should be markedly increase in near future when separate collection of textile wastes will become mandatory by 2025.

In Finland, basic textile production has been transferred to low-cost countries in Eastern Europe and Asia in recent decades. Still Finnish textile industry still values around 3.4 billion € (SITRA, 2015) since the design and product development are still being managed in Finland. Demand for sustainable textile materials is high and growing in Finland as well as in global markets, but there is shortage of such material, or available materials are too expensive or not suitable for all product types. Locally produced materials are not available currently.

VTT dissolution technology offers a new way for utilization of used cotton textiles as raw materials for new fibres. It is environmentally friendly way to utilization of discarded textiles not recyclable by other means. This technology provides local solution for utilization of post-consumer textile waste. Approach is in line with sustainability principle; it enhances raw material efficiency as well as reduces amount of waste. This topic was very current due to ban of organic waste from landfills in 2016.

Closed loop business models and circular economy in general are currently untapped opportunity for Finnish commerce and industry. Growing awareness of consumers produces demand for recycled materials and, thus, generates business potential in consumer goods markets. Answering new consumer needs and utilization of this potential requires co-operation of whole value chains. It also provides development of new business and service models, new logistic solutions and understanding new customer interfaces.

This report present summarised the results of TEKI project focusing on work carried out by VTT and summarizes all results obtained from common research activities, i.e. public part carried out with companies involved. Our consortium included actors from all stages of the value chain enabling practical implementation of post-consumer textile recycling pilot.

2. The Relooping Fashion Initiative

Circular Economy of Textiles / Tekstiilien suljettu kiertotalous (TEKI) -project also promoted publically as *The Relooping Fashion Initiative* focused on piloting and modelling the closed circular ecosystem for textiles. Such ecosystem lays a foundation for utilization of textiles and especially of the textile waste fraction currently not suitable for recycling in new way. Main themes of the project included service, production, design and business. The common goal of the organisations was to promote the recycling of textiles while adding value to their business activities or creating new business. Project was funded by Tekes – the Finnish Funding Agency for Innovation, as part of Green Growth program.

Circular economy is one of the Finnish Governments spearhead programs (Valtioneuvosto, 2017). Transformation from linear to circular business ecosystem requires changes in all business and industrial fields. Closed loop business models have many opportunities, but are still challenging for businesses (SITRA, 2015). TEKI project together with other similar projects can speed up the change in Finland.

2.1 Goals and Scope

The main goal of TEKI project was to pilot and model the closed circular ecosystem for textiles. Technical driver for the piloting was to be the first industrial scale closed loop post-consumer recycling system for cotton, which has scalability potential in international scale. Aim was to produce fibre to replace virgin cotton as well as synthetic fibres without deterioration of fibre quality.

Cellulose carbamate (CCA) process enable the utilization of that fraction of cotton textile waste, which cannot be reused as product, for example, broken and stained items, as raw material. This is in accordance with principles of waste hierarchy. Furthermore, CCA fibres can be produced using the same technique and equipment that has been used to produce viscose fibre for decades, but the new production technique is considerably more environmentally friendly than the technique used for viscose, as no carbon disulphide is needed in the dissolution process.

CCA technology is based on the knowledge built up within long term research activities at VTT including. Carbamate technology is based on existing IPR (e.g. Valta & Sivonen, 2002; Sivonen & Valta, 2005). Before the pilot VTT has successfully utilized cellulose carbamate process for dissolved pulp as well as recycled paper and board materials (Asikainen *et al.*, 2013; Heikkilä *et al.*, 2013) for production of environmentally friendly viscose-like fibres. Cotton pre-processing steps has also been developed at VTT (e.g. Asikainen *et al.*, 2012) and before piloting we successfully carried out a lab scale recycling demo using cotton as raw material within VTT's self-financed project. However, only scaling up the process into pilot scale enabled us to evaluate technological requirements and overall feasibility of dissolution-based recycling.

Modelling work aimed to produce description of actors, processes and material flow within closed textile recycling ecosystem as well as description of division of added value within ecosystem. Aim of the model was to find business opportunities and provide shared value for all parties within value chain. Circular model may be beneficial by securing long-term relationship with customers and create new value. Challenges of closed loop recycling of textiles include cost of reverse materials logistics, sorting and pre-processing. Also setting up of closed loop value chain is complex and requiring new approaches to businesses involved. Motivation for this kind of modelling work grew also from possibility to build up and model business ecosystem and this model may be transferrable also to other sectors or other regions.

Furthermore, we reviewed consumer habits and consumer communication as method for committing consumers to circular economy. Closed loop textile ecosystem requires active participation of consumers the loop since they make the demand and are the raw material provider for the business. Our aim was to gauge consumers' interest in operating models that are based on the principles of circular economy and recycled materials.

Project was expected to support sustainable business model development aims of participating companies. Its offered possibility to gain understanding of new type of raw materials and recycling processes. Understanding of consumer attitudes is important when planning communication of value proposition to the customers.

2.2 Implementation

Circular economy of textiles project was implemented as group of projects. Companies were able to develop their own processes, business models and/or products in their own projects, and participate the common, public part coordinated by VTT in co-operation with Ethica. TEK1 consortium (Figure 1) had in the beginning (1325/31/2015) seven partners and since spring 2016 (923/31/2016) nine partners. Five partners - VTT, Seppälä, Ethica, The Helsinki Metropolitan Area Reuse Centre (HMARC) and Repack - had their own Tekes-funded projects; two partners - Remeo and Pure Waste - participated in pilot without funded project; and two partners -Touchpoint and Lindström - joined in spring 2016, when VTT applied additional funding for the pilot (923/31/2016). All partners participated the public part of project work and many of them in pilot.

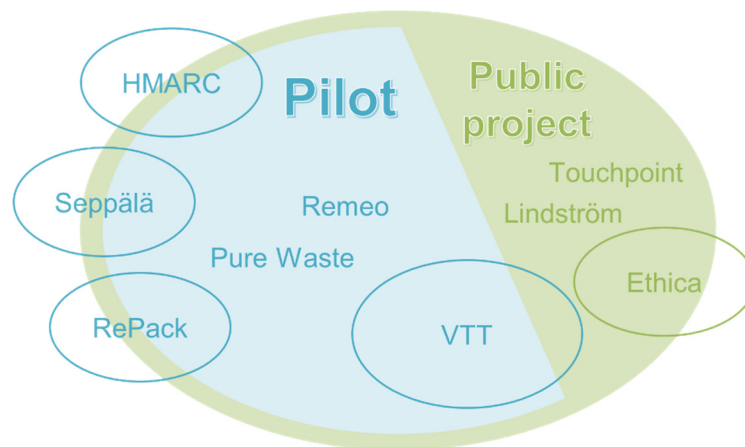


Figure 1 The Relooping Fashion Initiative contained public part (green), large part of which was the pilot (blue). It composed of five parallel projects (circles around participant names): VTT's project was public, while four company projects included also companies' confidential R&R work. Other company partners had a role in public project by providing work and/or funding

Common part reported here included four work packages (WPs): 1) circular economy pilot, 2) business ecosystem modelling, 3) consumer interface, and 4) technology. Description of work packages is presented in Table 1.

Table 1 Work package structure

No	Name (leader)	Main goals, activities and expected outcome
1	Pilot (VTT)	Aim was implementation of post-consumer closed loop textile recycling pilot. Tasks 1) Collection, sorting and pre-processing of materials, 2) Making fibres, 3) Production of textiles and proto collection. In addition to successful pilot and proto collection aim WP was to obtain material samples from all stages of the process and data for evaluation of technology in WP4.
2	Ecosystem modelling (Ethica)	Aim was modelling of circular ecosystem of textiles and as a result obtain description of that including actors, processes and materials flows as well as give preliminary evaluation of sharing of value.
3	Consumers (Ethica)	Aim was to collect information about consumer behavior and attitudes e.g. 1) how to guide public towards circular economy; 2) most preferred logistics for textile collecting; and 3) means for communicate with public about circular economy and recycled textiles.
4	Technology (VTT)	Evaluate feasibility of technology and pilot like business case. Tasks included also evaluation of suitability of CO-PES mixtures in recycling process and possibilities for use of produced fibers in different applications.

VTT's core competence in this project is cellulose carbamatization and dissolution process for cellulose carbamate. VTT's role in pilot consisted of dissolution and wet-spinning phases, and from technological side VTT evaluated technological possibilities for continuous operation of piloted process. VTT was also involved in workpackages led by Ethica: providing expertise and in-sight to business ecosystem modelling work and in consumer studies VTT carried out part of consumer study in VTT's Owela Open Web Lab platform.

This report summarises the work carried out in public project, thus, focusing on VTT activities. Chapter 3 summarizes work related to pilot (WP1) including also technology related aspects (WP4), Chapter 4 summarized ecosystem modelling (WP2), and Chapter 5 consumer studies (WP3). Furthermore, dissemination activities are described in Chapter 6, and summary of the results and conclusion given in Chapter 7. Report is public, but its annexes are confidential providing more details of the work carried out for the steering group only.

3. Piloting and Technology

The largest endeavour of the project was the circular economy pilot (see Figure 2). In the pilot, post-consumer textiles were sorted, and the used cotton textiles not suitable for reuse were turned into new man-made cellulose fibres through the dissolution and wet-spinning processes. The fibres obtained from lab and pilot scale trials were used for producing new textile materials, such as yarns, knitted materials and garments. The idea to close the loop was that clothing collection produced from recycled raw materials would be sold in re-usable packages. Consumers would have been able to return their old clothes to the recycling loop while returning the sales package, thus, closing the loop.

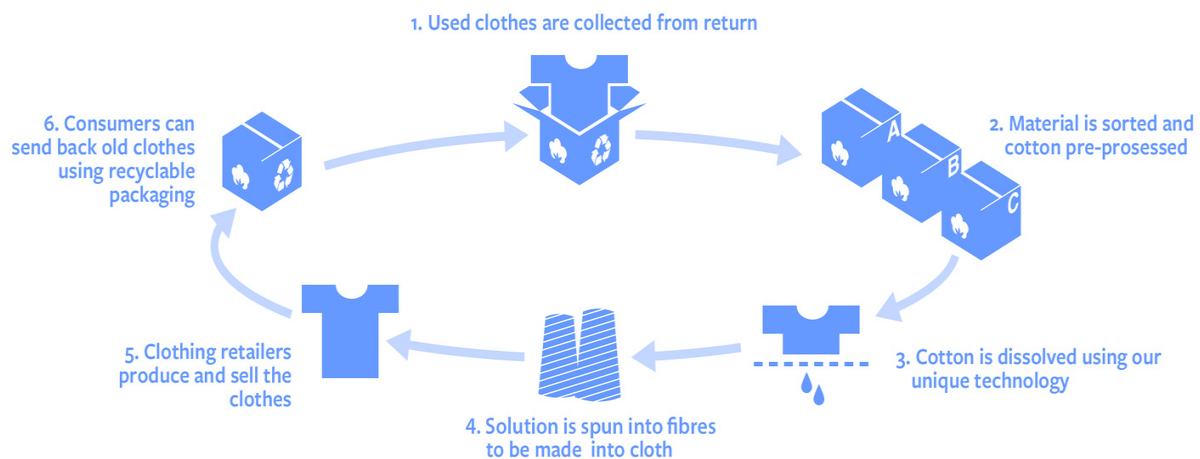


Figure 2 Principle of the closed loop-pilot

This latter part remained in idea level, since pilot was not realized from that part within TEKI project. Original plan was to do wet-spinning pilot within closed Valkeakoski viscose factory in 2015 (Figure 3a), but pilot scale spinning successfully realised somewhat later, in 2017, when pilot line was transferred in installed into VTT's Bioruukki piloting centre (Figure 3b). Work and results of pilot is summarized in following chapters, and more detailed description on VTT's work is included as an Annex 3 (confidential).

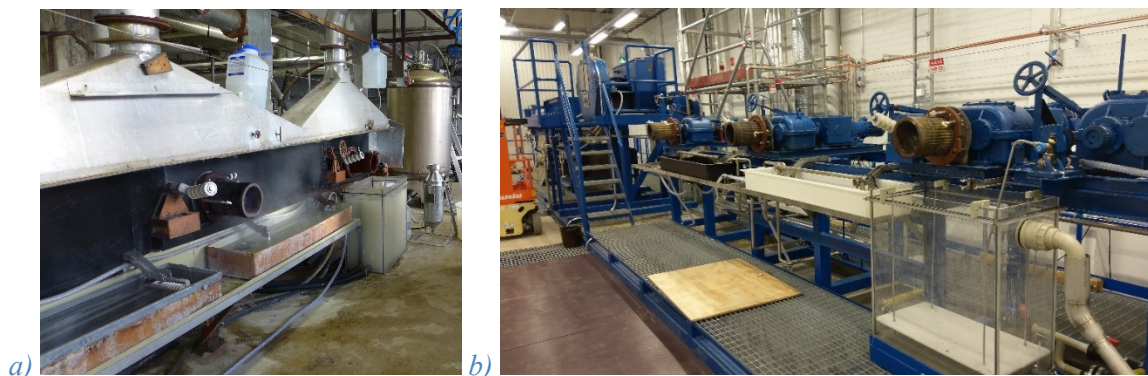


Figure 3 Wet-spinning pilot line a) in Valkeakoski closed viscose factory, and b) in VTT's Bioruukki piloting centre

3.1 Process

3.1.1 Sorting and Pre-Processing

First phase of the pilot was handling of raw materials. This included collecting and sorting of cotton textiles from discarded post-consumer textiles and mechanical pre-processing that into raw material suitable for recycling process.

First batch of materials came from normal material flows of the Helsinki Metropolitan Area Reuse Centre (HMARC), and collection of that started in the beginning of May 2015. Chemical pre-treatment trials consumed most of first material batch, and second batch of material was collected in winter 2015-2016. That batch contained also material from Seppälä's customers obtained from used clothes collection campaign organized in selected Seppälä stores in the January 2016. Trials were carried out also using this batch, but due to too high polyester (PES) content of the second batch we had to take third batch, with less contaminants. Third batch composed of post-consumer bed linen obtained also from HMARC. Bed linen have less seams and thus less sewing yarns compared to clothing, and they are thus less likely to contain PES from sewing yarns. However, it is possible to have few percent's of other fibre included into so called 100 % fibre without need to state that in label.

HMARC sorted all materials (see Figure 4). Sorting personnel of HMARC were advised to recognize typical cotton articles from flow and then check the labels from them. Cotton textiles that could not be reused as clothing or as material for recycled products were selected for the pilot. As first pre-processing step buttons, zippers and thick seams etc. were removed. Material was grinded by Remeo and/or by VTT. Appearance of material after coarse grinding is shown in Figure 4b.



Figure 4 a) Sorting of post-consumer materials in HMARC, and b) grinded textile materials

3.1.2 Chemical Processing and Dissolution

VTT was in charge of the second stage of the pilot including further mechanical processing by grinding, chemical processing of material to turn it into a cellulose carbamate solution and wet-spinning it into fibres. Chemical processing steps were carried out in reactors (example of which is shown in Figure 5a). Chemical processes included removal of silicates with NaOH, bleaching with ozone, alkaline treatment, and acidic treatment for removal of metals before drying. For the last material batch, chemical pre-treatment processes were carried out in pressurized conditions applying high temperature to remove PES residues from the mass. Pre-treated mass was then carbamatized using urea and NaOH in elevated temperature. Cellulose carbamate is dry intermediate product (see Figure 5b), which is stable in this stage, and can be stored while waiting for dissolution and spinning stages.

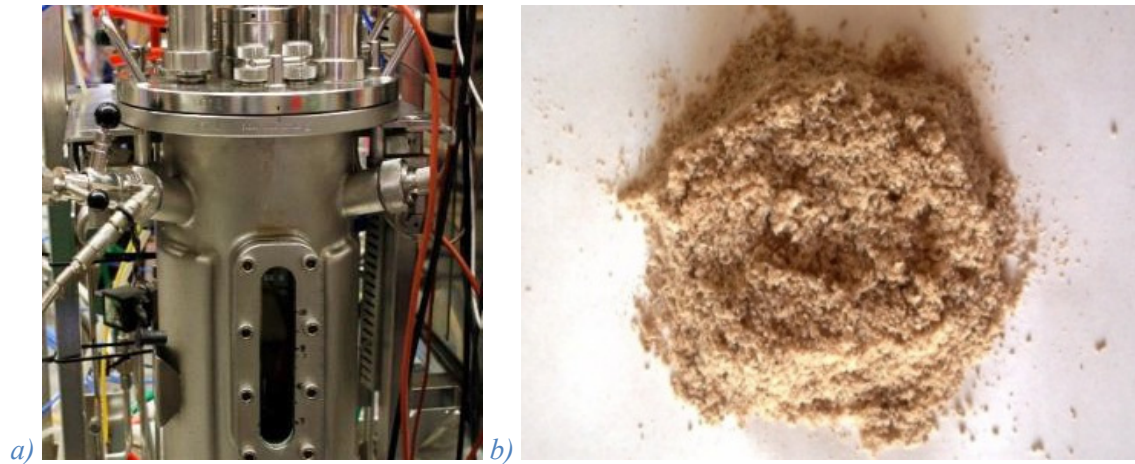


Figure 5 a) Reactor in Rajamäki used in chemical treatments, and b) carbamate cellulose intermediate product waiting for dissolving

Spinning dope is aqueous solution of NaOH containing zinc oxide. Dissolution was done in cold conditions. After dissolution the solution was filtered and gas removed. Filtration is a critical process step, if there are any PES residues in the material, as can be seen from Figure 6 showing microscope images of both unfiltered and filtered solutions. Since it is difficult to remove PES residues from the spinning dope by filtration – multiple filtration steps is required with higher efficiency filters – we adopted the alternative process for last raw material batch, which enabled recomposing of PES during the pre-treatments also. Dissolved CCA spinning dope is stable only limited time, and it needs to be wet-spun within one day or so.

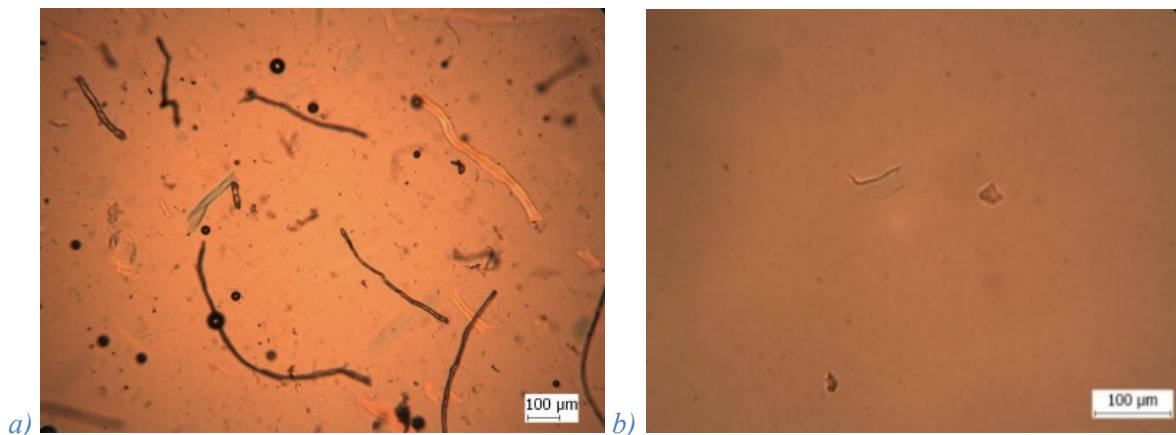


Figure 6 a) unfiltered solution containing PES fibres, b) filtered solution with material from which PES removed in pre-treatment.

3.1.3 Spinning

VTT carried out lab-scale wet spinning of CCA solutions; equipment used in trials are shown in Figure 7a. Fibre titre ranged from 2.1 dtex to 3.6 dtex, elongation from 14 % to 19 %, and tenacities from 1.3 cN/dtex to 1.4 cN/dtex with maximum tenacity being 2.0 cN/dtex. When produced in a small scale and process did not include bleaching, colour of the fibres varied from batch to batch (see Figure 7b).

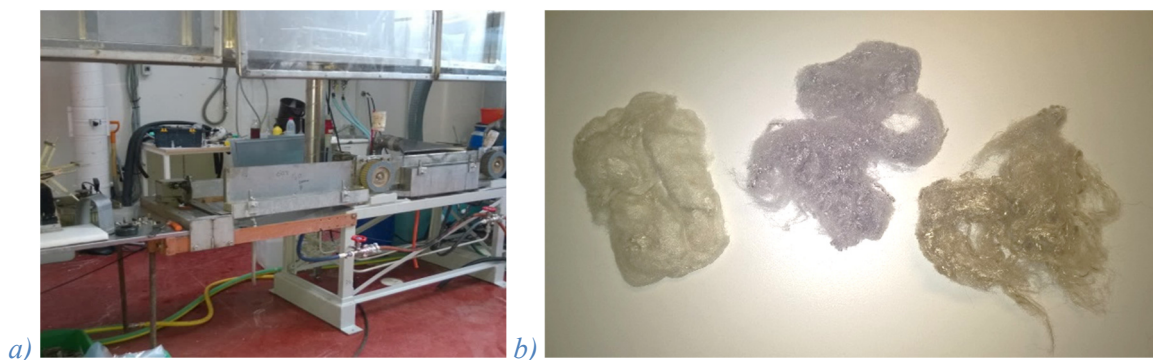


Figure 7 a) Lab scale wet spinning line, b) colour differences of un-bleached fibres from small lab scale batches

Pilot work ran into many problems and delays, and therefore process changes and various attempts needed to be taken before successful finalization of the work. As described earlier, we collected three material batches for this pilot, origin and processing of which was slightly different. These three batches correspond to also to our three attempts to go to Valkeakoski viscose factory: first attempt was in autumn 2015, second attempt in spring 2016, and third in autumn 2016.

During the first attempt we noticed that through put of our filtration system (used successfully in lab scale) was not sufficient to produce large enough spinning dope batches for Valkeakoski pilot plant due to low through-put of filter combined with limited stability of the solution. Therefore, we acquired two industrial scale filters for the second attempt.

Main reason for failing of the second attempt was too high PES content of the solution: we could not remove that at VTT Rajamäki, and our newly adopted filtration system also failed. One filter was faulty, but we also noticed that removal of PES with sufficient thought put would have needed more filtration units with tightening filtration capability. That is because PES was present not only as small fibre pieces (like in Figure 6a), but also on larger agglomerates, which readily blocked the tight filter materials reducing flow through the filters. With lowered capacity we would have again be facing stability limit of solution.

With third batch we used double means for tackling the PES, firstly, chemical process for its removal and secondly, multistep filtration of solution prior to wet-spinning. Piloting was not successful within TEKI funding, but was completed after moving pilot line to Bioruukki in 2017 with additional funding from TeKiDe¹ project. Altogether, 27 kg of CCA fibres was obtained from Bioruukki pilot runs. The realised titres were slightly higher that is consistent with the lab scale trials. Elongation at break of the fibres ranged from 15 % to 32 % and tenacity from 0.7 cN/dtex to 1.3 cN/dtex. The maximum tenacity of single fibre was from 1.0 cN/dtex to 1.9 cN/dtex. The elongation of fibres is higher and tenacity lower compared to the lab scale fibres.

3.2 Demonstration with Recycled Materials

3.2.1 Lab Scale Protos

The demonstrations for the feasibility of the chemically recycled CCA fibres for textile processing included the yarn spinning and knitting trials. Fibres from lab scale wet-spinning of the third raw materials batch were delivered to ring-spinning tests at Tampere University of

¹ TeKiDe, Taking fibre technologies towards industrial scale manufacturing, Spring 2017 – Autumn 2018, funded by the Helsinki-Uusimaa Regional Council's Structural Fund for Mainland Finland programme, the City of Espoo, VTT and Aalto University.

Technology. Two sets of CCA fibres, with fineness of roughly 4 dtex and 2 dtex, were first opened, and then carded twice. The carded webs were drafted to form slivers and the twice-drafted slivers were combined to form a roving, which was then spun into yarn with the ring-spinning machine. Mixing of mechanically recycled cotton fibres (obtained from Pure Waste Textiles) with CCA fibres were also tested. In that case, mixing was carried out during opening.

The chemically recycled CCA fibres performed well during the carding, the fibres did not stick on the rollers and carded web had enough cohesion indicating that the fibres had sufficient friction (fibre-to-fibre and fibre-to-metal) and crimp for the processing. This further indicated that the finishing of the fibres had succeeded. During the ring spinning the yarn twist had to be quite high in order to get strong enough yarn. With the lower twist than 600, the yarn was too weak to withstand unwinding from the ring spool. The finest possible yarn had the yarn number of 27 tex. It was possible to spin also finer yarns, however, the yarn breaking turned out to be so high that the loss of fibres during the spinning would have increased too much.

The mechanically recycled cotton fibres, delivered by Pure Waste Textiles, were a bit too short to be blended with the CCA fibres. The yarn spinning machinery was set for the fibre length of about 40 mm and as the length of the cotton fibres was clearly shorter, they did not perform well during the yarn spinning with the ring spinning method. Usually, in the ring spinning the fibre length has to be longer compared to for example open-end spinning.

Yarn samples were knitted with a lab scale circular knitting machine. The thinnest 27 tex yarn was too weak to be knitted as such, however, after doubling it the knitting succeeded. Knitted samples succeeded nicely 100 % CCA yarns with tex around 50. Knitting of mixed yarns mechanically recycled cotton fibres was not successful. It was too weak to be knitted with the circular knitting machine most likely due to the too short cotton fibres.

The industrial scale knitting demonstration was carried out from lab scale spun fibre with Agtavi. Agtavi produces knitted accessories such as stocking caps, mittens and gloves from wool, organic cotton and silk. The yarns from chemically recycled CCA fibres were knitted into gloves and additionally flat knitted fabric, Figure 8. During the flat knitting, the twist in the yarns turned out to be slightly too high as the yarns coiled and hindered the formation of the loop, thus producing holes. This was not such a big obstacle and nice flat knitted fabrics were produced from the yarns from 2 dtex CCA fibres and a mixture of 4 dtex and 2 dtex fibres.



Figure 8 Recycled CCA fibres and demonstrated products from chemically recycled cotton regenerated into CCA fibres

3.2.2 Pilot Scale Protos

Fibres obtained from pilot runs were sent to Pure Waste Textiles to be spun into yarns. Two type of yarns were produced by mixing chemically recycled CCA from Co to mechanically

recycled (mr) CO and thermally recycled PES, so called r-PET, from recycled bottles. Those were knitted into fabrics. Compositions and selected yarns and fabric properties of these are given in Table 2.

Table 2 Composition and properties of materials made from pilot scale spinning trails of CCA

Sample	Composition	Count	Yarn			Fabric grammage
			Tensile strength	Breaking tenacity	Elongation	
1	50 % CCA 50 % mr-CO	39 tex	3 N	0.08 N/tex	6.7 %	291 g/m ²
2	26 % CCA 26 % mr-CO 48 % r- PET	30 tex	5 N	0.17 N/tex	14.2 %	196 g/m ²

Appearance of yarns before dyeing and knitting in circular knitting machine are shown in Figure 9. CCA/mr-CO (50/50) blend was used in Anna Ruuhonen's design for Member of European Parliament Sirpa Pietikäinen's gala dress for Finland's 100 Year Independence Day Reception as shown in Figure 10.

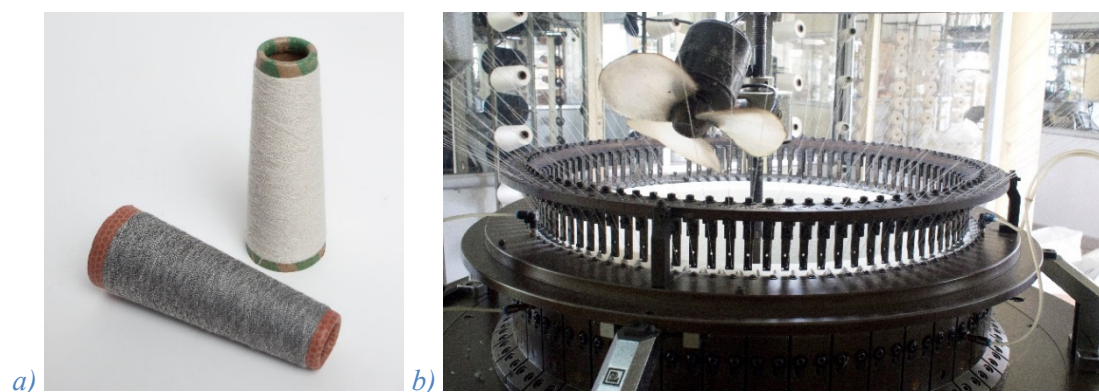


Figure 9 a) Appearance of mixture yarns utilizing pilot scale CCA fibres, and b) knitting in yarns at Pure Waste Textiles' factory

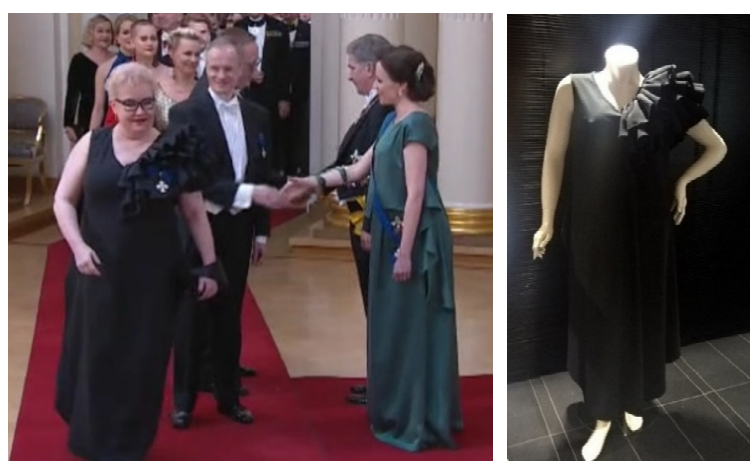


Figure 10 Evening gown designed by Anna Ruuhonen and worn by Sirpa Pietikäinen in 6.12.2017 Independence Day Reception

3.2.3 Properties and Possible Uses of Fibres

Cellulose carbamate technology is an attractive alternative for the preparation of regenerated fibres as cellulose carbamate dissolves in NaOH, and it can be processed by the wet spinning

technique using the same machinery as in viscose fibre production. Thus, the CCA fibres resemble viscose fibres and are possibly suitable for similar applications as staple viscose fibres. Viscose fibres are used for apparel and household textiles such as shirts, cardigans, dresses and ties, as well as blankets, curtains, sheets, tablecloths and upholstery textiles. They are also suited for hygiene and medical products such as tampons, absorbent pads for wound dressings, wipes, incontinence pads and nonwoven surgical gowns. Short cut viscose fibres are applicable for example for wet processing into speciality papers, cartons, filters, teabags and wipes. (Kelheim Fibres GmbH, 2017) Specialty high tenacity viscose is also used as tire cord as reinforcing material in tyres.

Based on the processability of the chemically recycled CCA fibres during the demonstrations, the fibres proved to be suitable for the yarn spinning and knitting of fabrics and thus they are suitable for the production of apparel and household textiles. Clothing applications from gloves to t-shirt and evening gown were also showed in demonstrations.

The fibres performed well also during the carding indicating that they can be processed into nonwovens (even this was not demonstrated). Nonwovens from viscose fibres are used in the medical and hygiene sector and are approved to be toxicologically and physiologically not harmful. Based on their processing performance, recycled CCA fibres are suited also the hygiene and medical sector, however the product safety issues needs to be clarified and the fibres needs to have an official approval.

In the chemical structure of CCA fibres, there is carbamate substituents in some the hydroxyl groups (OH-groups) of cellulose molecule; however, the degree of substitution is so low that there are free OH-groups that can interact with water. The absorption of water and moisture allows also the absorption of perspiration thus making the fabric breathable and comfortable. For the same reason, it does not build static charges. Based on the chemical structure, the recycled CCA fibres can be dyed with the dye groups suitable for cellulose such as reactive, vat, sulphur and direct dyes. The good water absorption indicates good dye exhaustion that can be connected to the good fixation of the dye. The matt colour of the recycled CCA-fibres may hinder the dyeing with bright colours without bleaching, but then the matt colour may suit to some applications without dyeing.

The flat knitted fabric made from the recycled CCA fibres is smooth with a subdued matt finish and drapes nicely. It would suit well for the production of knitted clothing such as cardigans, knitted vests and skirts. For this kind of applications, the textile care labelling is needed. The instructions and recommendations are well documented in SFS-guide (*SFS-opas 3 Tekstiilien hoito-ohjemerkinä. Käytännön toteutus*). The guide supplements Inspectas's guide, TSL 23-901, and the SFS-EN ISO standard 3758. It covers the domestic washing treatments for textiles such as washing, bleaching, drying and ironing. In addition to the washing temperature, an important test for a knitted cloth is the measurement of the dimensional change in washing (SFS-EN ISO 5077). With the help of these tests and instructions, one can provide information on the most severe treatment that does not cause irreversible damage to the article during the textile care process.

3.3 Techno-Economic Aspects

One aim of the project was to define prerequisites enabling the process we piloted as commercial operation in Finland. Evaluation of techno-economical aspects included availability of determining the value chain and maturity of the technologies needed (3.3.1), economic (3.3.2) as well as environmental evaluation (3.3.3) of the process. Furthermore, we evaluated use of cotton polyester mixtures as raw material for the process (3.3.4). Some parts

of the work were carried out within CCA commercialization project RepoTex² which was conducted parallel to TEKI.

3.3.1 Value Chain and Maturity of the Technology

Main production steps within value chain for chemical recycling of cotton are shown in Figure 11. Raw material collecting and pre-processing steps are currently missing and needs to be established in order to make this viable process. Collection of textile wastes can be established relatively easily, but economics of such collecting system as well as sufficient quality identification of fibres and fractionation of cotton from other fibres and blends are more of the challenge. Existing recognition systems include NIR, however, there is not much experience in high speed recognition and sorting facilities capable of production of sufficient amount of pure enough cotton for full scale industrial production of these fibres yet. Telaketju project³ will tackle some of the collecting, sorting and raw material quality issues.

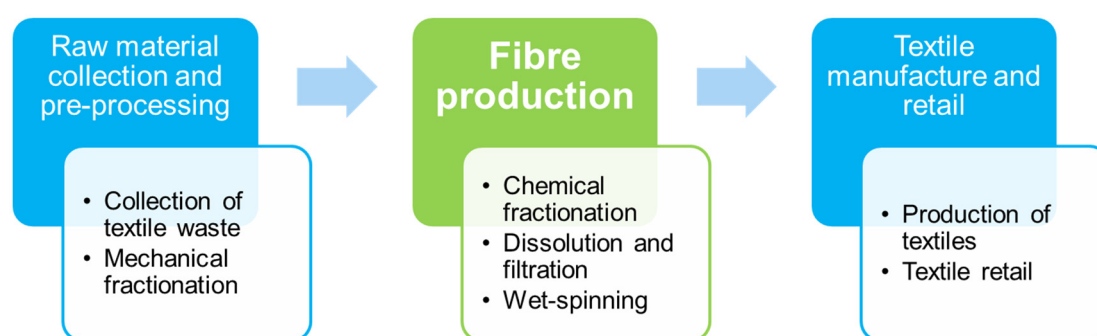


Figure 11 Cotton recycling into new textile fibres: production structure and its main stages (RepoTex, 2017)

TEKI project focused on fibre production step. We had challenges in taking CCA based recycling process into pilot level in our project, however, most of the technical issues were related to available facilities (reactor sizes, filtration capacity etc.) and, thus, should not be too difficult to overcome in pilot factory. Chemical fractionation and processing of cotton is VTT technology, which will be now further developed by IFC. Fibre spinning can be carried out with existing wet-spinning setups available currently for viscose fibres.

Textile value chain is typically long, and after production of fibres, it includes production of yarns and fabrics as well as sewing of garments and other textile products followed by logistics, distribution and sales. These step followed by fibre production can utilize existing ecosystem.

Summary of maturity of key process steps from raw materials to fibre production is shown in Table 3.

² Business from chemically REcycled POst-consumer TEXtiles, Tekes/TUTL, 2015-2016

³ Telaketju, Tekstiilien lajittelu- ja hyödyntämisketju, Tekes/Business Finland and Ministry of Environment 2017-2018, www.telaketju.fi

Table 3 Technology Readiness Levels (TRL) of key process steps

Process step	TRL	Description
Separate collection of textile wastes	5-6	Separate collection experiments have been carried out in Finland, but there are not yet permanent infra for this.
Manual sorting of textiles	9	Existing e.g. in Germany by SOEX
Manual sorting with sufficient quality for chemical recycling	3-(6)	Manually sorted cotton textiles for TEKI pilot contained impurities, amount of which was challenging in lab. (May be overcome with developed process).
Automated recognition of textile fibres	7-8	NIR has been shown efficient for recognition of fibres. Commercial Fibersort is based on that technology. http://www.valvan.com/products/equipment-for-used-clothing-wipers/sorting-equipment/fibersort/
Efficient automated sorting	7	Lahti University of Applied Sciences has a lab scale sorting machine, pilots in Siptex (SE) and Fibersort (NL)
Mechanical pre-treatment of CO	6	Lab scale to lab pilot scale processes used in TEKI project
Chemical pre-treatment of CO	6	Lab scale to lab pilot scale processes used in TEKI project
CCA fibres from recycled CO	5	Lab scale to lab pilot scale processes used in TEKI project
CCA fibres from dissolved pulp	8	Industrial pilot trials carried (e.g. Aviron)
Wet-spinning of regenerated fibres	9	Viscose process commercially available for centuries

3.3.2 Economics of the Process

Economical evaluation of the process was carried out by group of students of Aalto University (Aki Henttonen, Reetta Hassinen, Iiro Perttula, Henri Harlin), who used our case in their practical work related to course CHEM-E7200 *Design Project in Chemical Engineering*. This was part of RepoTex project.

In these economic calculations raw material was considered textile waste of which around 30 % was considered to be cotton. Sorting out textile waste were raising the costs for raw material, and mixed fabrics were considered as a problem for the process. Process included pre-treatment, carbamation, dissolution and spinning of fibres. Main product of the calculated process was staple fibre consisting cellulose and having properties close to viscose staple fibre.

Economical calculation indicated that investment of around 35 M€ is needed and almost break-even case can be obtained with selling price of 2180 €/t, which is slightly higher than price of viscose and cotton. Better economics can be expected if fibres are used in well-branded, recycled product or if cotton prices will rise e.g. due to weak crops. Investment payback time was estimated to be 6 years. Investment and manufacturing costs are shown in Table 4, and division of operating costs in Figure 12. More detailed information of economic calculations are given in Annex 5 (confidential).

Table 4 Investment and operating costs of CCA process

Factors		Cost
Investment decision factors	Fixed capital investment	34.9 M€
	...of which equipment cost	10.5 M€
Manufacturing costs	Operating costs	1630 €/ton
	Production costs	2170 €/ton
Prices of competing products	Viscose	~1900 €/ton
	Cotton	~2000 €/ton

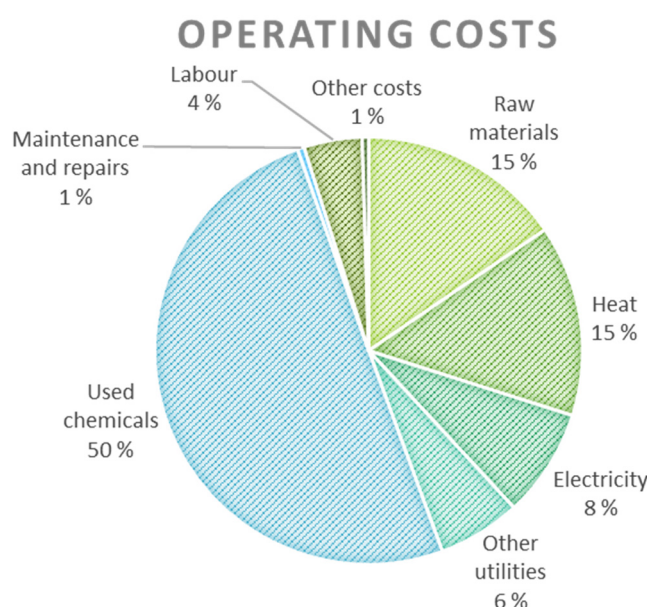


Figure 12 Division of operating costs of CCA process

3.3.3 Environmental Aspects

Leena Katajainen from University of Jyväskylä carried out life cycle inventory (LCI) evaluation of the process as part of her graduate thesis about of cellulose carbamate process (Katajainen, 2016). Global warming potential (GWP) (CO₂ eq.) for CCA factory with some variations was calculated and compared with viscose and cotton.

First case (CCA1) was based on Aalto factory design, within second (CCA2) circulation of some chemicals and water were included, and in third one (CCA3) in addition to circulation, recover of NaOH and H₂SO₄ back to circulation included. Inclusion of chemical and water circulation to process and further inclusion of recovery of NaOH and H₂SO₄ reduced the need of NaOH by 36 % and 85 %, respectively. Furthermore, these changes recused need to H₂SO₄ by 48 % and 88 %, but recovery step increased the need of electricity significantly, by more than 500 %.

GWP of processes were calculated with (stand-alone factory) and without heat energy (integrated factory), see Figure 13. CCA process gets the lowest GWP value with chemical recovery (CCA3), and integration of factory had large effect on GWP compared to stand alone factory. GWP of CCA3 from integrated factory (~1900 kg CO₂ eq.) (Katajainen, 2016) has GWP similar to viscose (1800) produced by Lenzing in Austria, and significantly less compared to Asian viscose (5800) and cotton (3040) (Shen & Patel, 2010).

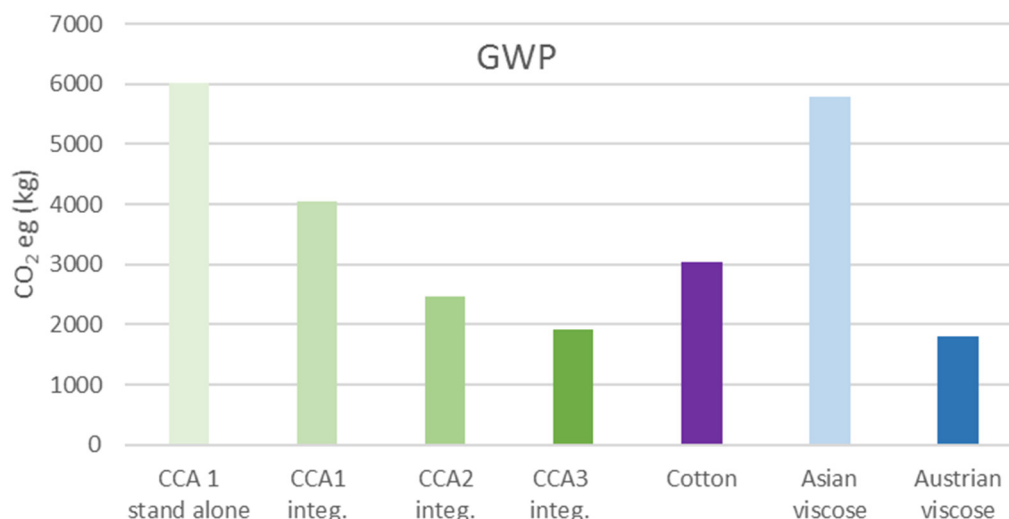


Figure 13 Global warming potential of CCA process variations (Katajainen, 2016) compared to cotton (van der Welden et al., 2013) and viscose (Shen & Patel, 2010)

It should be noted that GWP is only one indicator used in evaluation of environmental aspects of the products and/or processes. CCA recycling process would show more benefits compared to competing fibres, if evaluated with wider scale of LCA indicators. Viscose process, for example, has CS₂ that is highly toxic, but its impact to environment is not shown in GWP. Water use off CCA process per kg of fibre, on the other hand, is just a fraction of that used for cultivation and production of one kg of cotton fibres.

3.3.4 Suitability of PES-CO Blends as Raw Material

PES impurities caused some challenges in our pilot, but since many textiles compose of cotton/PES mixtures we evaluated possibilities of use these mixtures as raw materials. Separation of cotton and PES from blends can be done mechanically, by molecule recovery or by extraction. In mechanical process blends are broken down into fibres before sorting and theoretical recover rate of is approximately 80 %. In molecular recovery cotton is broken down into sugars, which can be used for ethanol production, and PES is broken down to purified terephthalic acid (PTA) and pyro-oils. Efficiency of the process is unknown, but theoretically recovery rate can be approximately 67 %. (Harlin, 2017)

The extraction routes have been studied world-wide. In extraction PES and/or cotton can be recovered by dissolving or recomposing one component out from their blend. Recovery rates for PES and cotton can be as high as 90 % and 65 %, respectively. PES can be used for production of new fibres by melt-spinning if polymer quality is sufficient, but polyester can also be chemically decomposed at the molecular level and then converted into new polyester raw material. Polyester recycling processed suitable for closed loop recycling of PES textiles are, for example, Eco Circle process by Teijin (Palm, 2014; Teijin, 2017) and Patagonia processes (Zamani, 2011). Cellulose obtained from cotton for production of regenerated fibres using cellulose carbamate, viscose, lyocell, Biocelsol or Ioncell processes. (Harlin, 2017)

European commission is funding projects targeting for utilization of textile wastes. RESYNTEX is a research project, which aims to create a new circular economy concept for the textile and chemical industries. Using industrial symbiosis, it aims to produce secondary raw materials from unwearable textile waste. They aim to demonstrate a complete reprocessing line for basic textile components, including liquid and solid waste treatments. (Resyntex, 2017)

Thash-2-Cash project aims to produce high quality materials from cotton and polyester textile as well as paper wastes, and product prototypes from waste, offering companies in various

industries (fashion, interiors, automotive and other luxury goods) new eco-fibre options. (Trash-2-Cash, 2017) Extraction route examples from the literature are listed in Table 5.

Table 5 Possible methods for separation raw materials from PES-CO blends

Material to be recovered	Principle	What is obtained	Reference
Cellulose	Solubilisation of cellulose by a mixture of glacial acetic acid and acetic anhydride	Cellulose acetate	US Patent 3937671
	Solubilisation of polyester by various organic solvents, e.g. a sulfone solvent	Cellulosic fibres	e.g. US Patent 5342854
	Degradation of polyester by alkaline hydrolysis	Cellulosic fibres	US Patent 3801273
Both	Selective hydrolysis of polyester in NaOH solution and selective dissolution of cellulose in NMMO	CT for new PES polymerization and lyocell fibres	Negulescu <i>et al.</i> , 1998
	Degradation of cellulose by acid hydrolysis	Cellulosic powder, microfibrillar PES	e.g. US Patent 3937675
PES	Degradation of cellulose by enzymatic (Trichoderma reesei, Cellusoft L) treatment	Microfibrillar PES	

4. Business Ecosystem Modelling

The goal of the business ecosystem modelling was, firstly, to crystallize the future vision of circular economy in textiles industry, and secondly, to define different actors, material flows and key processes in the wider cross-sectoral value network. Looking at the business ecosystem from the many different perspectives based on the circular economy principles (the value circles, circular business models and circular design strategies) increases the understanding of all different means needed in the transition towards a circular economy. Crystallizing this common high level vision, and clearly articulated customer value proposition are key success factors in the birth stage of new business ecosystems. (Fontell & Heikkilä, 2017)

Our vision of the circular business ecosystem of textiles is based on the four value circles familiar from the circular economy system diagram by the Ellen Mac Arthur Foundation (shown in Figure 14).

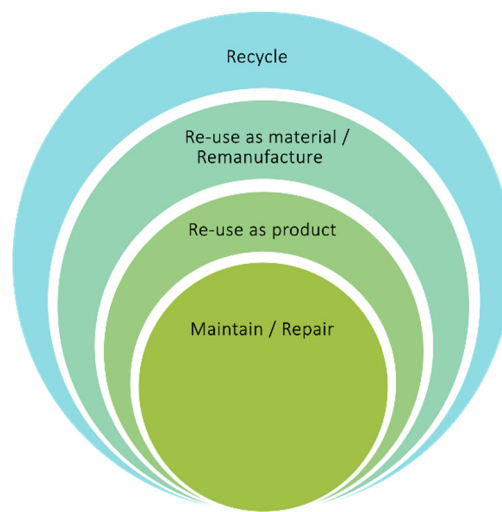


Figure 14 Four value circles of circular economy (Fontell & Heikkilä, 2017), simplified from (Ellen MacArthur Foundation, 2017)

4.1 Modelling Work

The scope of the business ecosystem modelling work was wider than the actual circular economy pilot, which focused on the chemical recycling cycle. Widening the scope was necessary in order to ensure that the material flows follow circular economy principles and waste management hierarchy. The other cycles already exist, while recycling cycle is not yet functioning to its full capacity. Less emphasis was given to the textiles and clothing industry from fibre production onwards, although some key findings are highlighted for that part of the value chain as well.

The business ecosystem modelling work was based on experiences and the vision of the national business ecosystem in Finland, but also other international initiatives were studied. The achieved results are somewhat applicable globally. The research did not represent a full global view on the circular economy of the textiles industry, and did not aim to cover all on-going initiatives world-wide. Modelling work was carried out via literature studies, project workshops and individual interviews of the project partners as well as selected other local stakeholders working with the textile business and recycling.

The simplified model describes in high level the main material flows from one actor to another along the value chains. Although business ecosystems are very complex in detail, our modelling work focused on illustrating the high-level vision of the future ecosystem; the needed actors,

their roles and their interdependencies in terms of the main product/material (used textiles) flows. The model is illustrated in Figure 15.

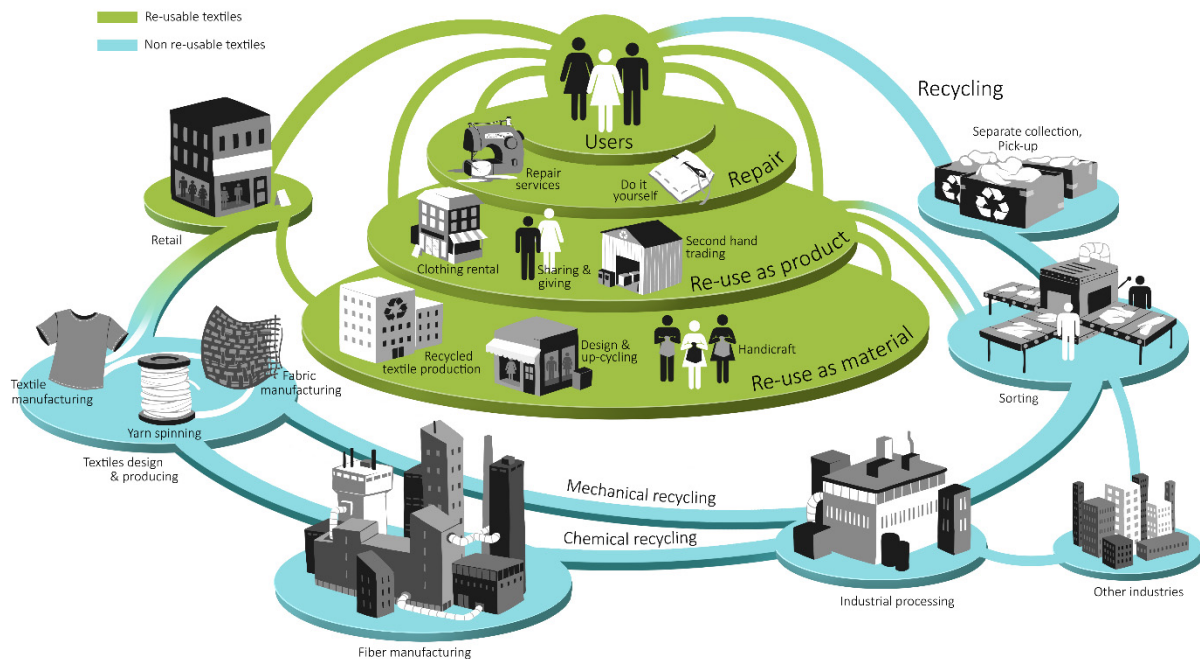


Figure 15 Model of circular business ecosystem for textiles (Fontell & Heikkilä, 2017)

Selected parts of the circular business ecosystem model, those relevant to TEKI project partners, is explained in more detail within separate report (Fontell & Heikkilä, 2017). These are:

1. The loops for re-usable textiles
2. Re-usable textile loops in B2B business
3. Textile collecting and sorting
4. Producing recycled fibres
5. Textiles from recycled fibres

That report gives an overview of the guiding principles and the key functions, actors, and related business models for closing the loops. It also include section related to shared value, which is based on work done by Essi Becker as part of her thesis (Becker, 2016). This ecosystem model lays a foundation for reuse and recycling of textiles, focusing especially on the post-consumer textile waste fraction currently not suitable for recycling.

4.2 Summary and Conclusions

“Transition to a circular economy is a systems-level change and requires a new kind of value creation mind-set. Designing out waste and maintaining the value of products and materials as high as possible for a maximum period of time, requires close collaboration among the whole value network. That is why business ecosystems are at the heart of the transition to a circular economy. Circular business ecosystems are business ecosystems, which together create products, solutions and services based on circular economy principles, and apply circular business models in their way of operating and doing business.” (Fontell & Heikkilä, 2017)

Summary and conclusions by Fontell and Heikkilä (2017):

“The four hierarchical loops of the circular business ecosystem of textiles all start from users, whether consumers or professional users. Users, with their values, attitudes and most importantly their behaviours are the key enablers of all those processes. The first goal for textiles in a circular economy is to be able to use textile products in their original format for as long as possible. A key enabler for that is circular product design; clothes should be designed to last and maintain good fabric quality. With the right user behaviour, as well as maintenance and repair, clothes and textiles can be used for the maximum length of time. When the user for any reason wants to stop using the clothes or other textiles products suitable for re-use as a product, they should be redistributed to other possible users.

The next-preferred option for clothes and textiles that are still suitable for re-use, but no longer in their original format, is to use them as textile materials. Only when the quality of the fabric is such that it is no longer suitable for re-use, should the clothes and textiles be recycled to be used as raw materials for new products.

One of the biggest issues to solve for a circular business ecosystem for textiles, is the collection and sorting of textiles, especially those no longer suitable for reuse. Those collection methods should be as easy as possible for the users. Home pick-up is the easiest, and one of the most preferred options from the consumer perspective, albeit not financially efficient until there will be effective reverse logistics systems in place.

In the future circular model, users should be able to determine whether discarded clothes that they no longer use could still be re-used as a product, or whether they should be recycled. However, we see that currently the users are not sufficiently able to do that, which indicates a need for better instructions, awareness raising and collection methods. Even if consumers would in the future be better at sorting the textiles for recycling, it is important to establish a professional sorting standard based on quality of the product, and the type of fibre for enabling industrial- scale utilization. In addition to accuracy, sorting needs to be carried out economically.

As long as virgin materials prices are low, also the cost of sorted raw material for recycling has to be low, or the costs of sorting need to be covered by some other means. Industrial processing also requires removal of parts such as buttons and zippers, and refining of the fabrics according to the use specifications. The main material flows that can be identified from industrial processing to new fabrics include mechanical recycling of fibres either to nonwovens, or to yarns and further knitting and weaving, and chemical and thermal recycling methods of fibre raw materials for new fibres.

Mechanical, fibre-level recycling is possible for both synthetic and natural fibres and these processed are used around the world even though these volumes could be larger. In chemical and thermal recycling, fibres are broken down into their building blocks and new fibres are produced so that the length and strength of the fibres can be restored. Thermal recycling is applied commercially in small scale for synthetics, but the chemical process for cotton from cellulose is a widely studied emerging technology. Technologies available for using this cellulose as raw material for man-made cellulosic fibres include commercially available viscose and lyocell processes, as well as development-stage processes of cellulose carbamate (CCA), Biocelsol and Ioncell. There is a huge need for chemical processes for handling larger volumes of poor-quality textiles and possibly also impure materials. Water–sodium hydroxide solvent-based technologies, viscose, CCA and Biocelsol, can utilize existing viscose wet-spinning facilities, while lyocell and

Ioncell processes have their own requirements, and recycling of solvent. Currently, most of these processes are studied to enable used-cotton as a raw material.

The growing interest among the textile industry, and more specifically the biggest consumer clothing producers and brands, towards recycled textiles, is the key driver for developing new recycling technologies. This places the brands and retailers, who are close to consumers, in a central role in the circular business ecosystem of textiles. Being also closely involved in the R&D initiatives for the new recycling techniques, brands are getting a bigger role in fibre production as well.

Setting up the circular material flows will shorten the value chains, because brands will have to work very closely with all the actors of the entire business ecosystem. The retailers and brands will in the future also increasingly apply new circular business models, which are based on product use, rather than sales.

Furthermore, brands and retailers are in the key position in defining the new circular customer value proposition – which is central for the profitability of the new circular business models of all business ecosystem actors. The price of the recycled end product is an extremely important factor, when textiles made of recycled fibres are expected to reach the mass market – not only the environmentally conscious niche consumer segments. This is a central challenge for textiles recycling, as long as the prices of virgin materials remain low.

On the other hand, the low prices and often also low quality of so called “fast fashion” encourages the persistence of our current unsustainable buy, wear, throw away consumption habits, whilst in a circular economy, products should be designed to last. The low prices of fast fashion can only be explained by the power asymmetries of the value chain leading to competitive pressure to produce at the lowest possible cost, despite the negative economic, environmental, and social impacts. Products that are designed according to circular economy principles, such as the Cradle to Cradle standard, are sustainable by design, because social sustainability, like working conditions, is also considered.

Looking at our vision of circular business ecosystem of textiles, the circular economy has great potential for shared value creation. During the business ecosystem modelling work, that remained as a key guiding principle, although the research was not extensive enough to study the topic in detail. Furthermore, it is yet difficult to predict how the shared value-related objectives will be realized in future circular business ecosystems. Some of the key potentials and key challenges for the shared value creation are introduced in this report, concluding the report with the importance of a new value proposition for circular textiles.

The main direct opportunities of the circular economy relate to resource efficiency, the possibility to replace and reduce the usage of virgin materials, elimination of waste, new opportunities for employment, business and innovation, as well as promotion of sustainable consumption habits and fostering socio-economic well-being.

For reaching real impact, new textile products based on recycled materials and fibres should not stay as luxury products affordable only to few. Recycled products should be available and affordable to the mass market, but at the same time the emotional engagement for the products should be elevated, so that consumers are willing to take good care of them, and use them longer. The quality of the fabric has to be high, so that the products last and can be re-used before being recycled.

All those superb technical qualities, along with the material health, shared value, and overall sustainability of the products, should be at the heart of the newly defined value proposition for circular textiles.

The transformation from a linear economy to a circular economy has been started in the textile sector, but as we know there are certain parts still missing. A lot of work still needs to be carried out in Finland in order to enable more efficient utilization of discarded textiles and materials. One outcome of The Relooping Fashion Initiative was the starting of a new action, Telaketju, which aims for better utilization of textile waste and other discarded textiles by launching simultaneous actions in textile collection and sorting, as well as processing and product development. The ecosystem modelling work has crystallized many important success factors for circular business ecosystem of textiles. Those are, for instance, the importance of a shared systems level vision, inclusion of many different actors along the value cycles, and the formation of a well-articulated new value proposition for customers.

Collaboration is crucial, so that the necessary investments can be made to scale up the actions towards a circular economy. Consumers are ready, brands are interested, and several parts of the puzzle are being solved. It is our planet that can no longer wait. We hope that this report gives further courage to the increasing number of stakeholders to take the necessary next steps and speed up development towards truly circular textile products available for all.”

5. Consumer Interface

Aim of this WP was to collect information about consumer behaviour and attitudes e.g. 1) how to guide public towards circular economy; 2) most preferred logistics for textile collecting; and 3) means for communicate with public about circular economy and recycled textiles. Scientific publication has been written from the results of this WP (Vehmas et al., 2018), this is shortly summarized in this Chapter. Results of Owela studies carried out by VTT is included in more detail as confidential Annex 4.

5.1 Consumer Study

The research questions (RQ) in this study were:

RQ1. What are the consumers' views on circular garments?

RQ2. How should the remanufacturing process be communicated to encourage consumers to choose circular garments?

The research methodology consisted of interviews, an online innovation platform and workshops with project partners and external stakeholders, summarized in (Table 6). This research utilises a qualitative design to explore consumer perceptions of circular clothing and their marketing

Table 6 Summary of the methodologies used in consumer behaviour research.

Method	No. of participants	Focus group	Topic
Interviews	5	Finnish consumers	Consumers' views on sustainability issues in the fashion industry, second-hand vs. circular clothing, communications & marketing of circular fashion.
Owela	50	Finnish consumers	Consumers' motivation in recycling and communication.
Internal workshop	5-10	Project partners	Ideas and material for communicating and marketing circular products and services.
External workshop	18	External stakeholders incl. communications, marketing and textile professionals	Developing further the 'anchors for circular narrative'.

5.2 Summary and Conclusions

Consumer study was summarized and concluded by Vehmas *et al.* (2018):

"The time is ready. Consumers and companies are aware of the limited natural resources and climate change and concerned about the challenges they cause. It is understood that something needs to be done. Novel technological solutions for a more sustainable and closed-loop system have been developed for the textile industry, and new sustainable and circular brands are coming to the market. The closed loop system, where garments are recycled into new fibres, is quite a new phenomenon and a new business opportunity.

In this study, we reviewed consumers' views on circular garments (RQ1). Consumers really like the idea of recycling textile waste to produce new clothes. Finnish consumers more commonly return the clothes for reuse than throw the old garments away and they would be willing to return their textile waste to a separate collection point as they do with

paper, metal and glass. The attitude towards circular clothing is positive. Circular clothing is seen basically as new, and in that sense those who would not wear second-hand clothes, would happily buy circular garments. Circular garments should be more available on the market, and they should be branded as luxury items and a special edition that would be easily recognisable.

Even if consumers are interested in taking care of the end of the life cycle, they are not actually so interested in the beginning of the life cycle. And, even if consumers are interested in environmental and ethical issues, and they have the facts about manufacturing and working conditions, these do not usually affect their buying decision. More information presented in an attractive way needs to be provided to increase consumers' knowledge and willingness to buy sustainable clothing.

Communication has a remarkable role in convincing consumers of the importance of sustainable consumption. This study aimed also to clarify how the remanufacturing process should be communicated to encourage consumers to choose circular garments (RQ2). Obviously, more information about the environmental and ethical aspects of the textile manufacturers and brand owners should be available and communication should be more visible. Consumers also expect more concrete information regarding how their behaviour has affected, for example, the decrease of waste or the use of poisonous chemicals and hoped to see the results that have been achieved. Here, storytelling was seen as a useful way to share this information. Consumers expected neutral and fact based information, even humoristic, but preferred to avoid drama in the communication. Transparency of the production process is crucial to gain consumers' trust. All communication channels should be widely used in marketing. The role of web and social media channels has increased lately, but exploring different marketing styles is a must.

Feedback from the focus groups emphasised the need for value-added new services. Various services linked to circular clothing could create additional value for the consumers. Servitisation and digitalisation enable novel service development. Digital technologies have become more integrated across all sectors of our economy and society, and they create novel possibilities for economic growth (Vehmas et al., 2015). However, it is important to understand the needs and expectations of the consumers and use them as a starting point for service development. The best outcome will be achieved when developing the future services with the end-users. The service element needs to be included in the product design and business model from the beginning (Niinimäki, 2017). Cultural differences in using second-hand clothing are significant (Xu et al., 2014), but it can be expected that the difference is not so important in circular clothing.”

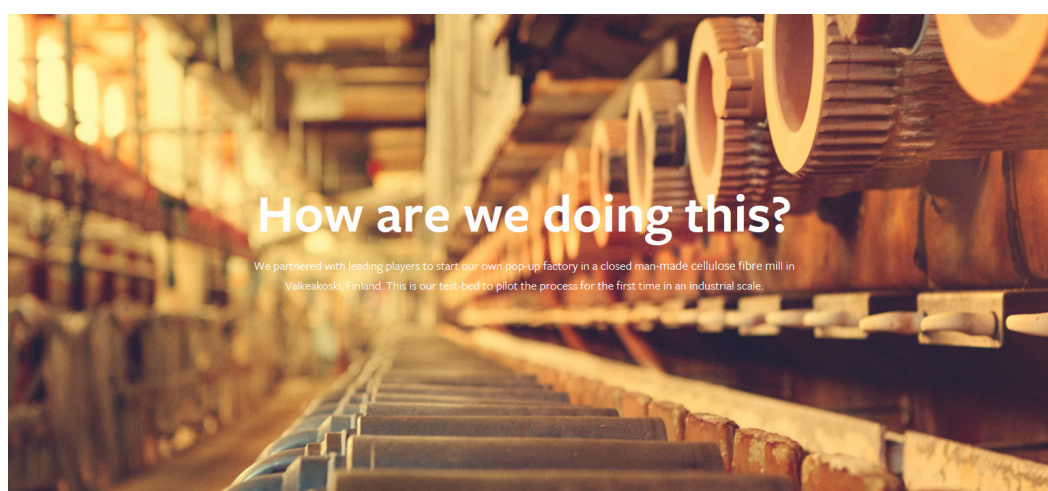
6. Dissemination Activities

Dissemination activities of the project included active communication about the project, publication of project results as well as networking and activities related to utilization of project results in order to obtain business opportunities for project partners and Finnish society. In addition to our own communication efforts, our project was noticed by media in Finland as well as abroad. More detailed list of communication activities of partners including also media hits are listed in Annex 6 (confidential).

6.1 Communication and Publication of Results

In order to gain as much publicity benefit from the project as possible most partners were very active in communicating about the project and their own endeavours towards sustainability.

Web site and newsletter. The Relooping Fashion Initiative published web pages (<http://reloopingfashion.org/>), and there was opportunity to leave contact information for our project news. During the project altogether 262 persons left their contact information to the page. We send altogether four *Relooping News* -newsletters (2.3.2016, 8.7.2016, 20.3.2017, and 30.10.2017) communicating status of the work and news from our partners to the email list including our project group, advisory board members as well as people who had submitted their contact information via projects' web page.



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This is a great example of the brilliant opportunity that the Circular Economy brings to European businesses. By creating new technology and innovative products for the future, we promote competitiveness and sustainable growth.

— Vice-President Jyrki Katainen, European Commission - Jobs, Growth, Investment and Competitiveness

Figure 16 Some content from project web pages (<http://reloopingfashion.org/>)

VTT's PR activities and Media releases. Project group together planned a series of videos. First one was produced by TEKI project and it was released in autumn 2015. Link to it is on our website, and it is also available in YouTube (<https://www.youtube.com/watch?v=xa-E2Re3bDE>), where it has obtained over 5000 views by the end of project (12/2017). Second video will be released after the end of the project. Its production is not included into project budget, but partners have been given their input to it.

VTT sent altogether six media releases about the project, which all obtained attention and lead to several media hits each.

- Starting phase of the project (22.9.2015)
<http://www.vtt.fi/medialle/uutiset/ainutlaatuinen-tuotantokoe-käynnissä-poistopuuvillasta-uutta-kuitua-muotiteollisuudelle>
- About the first delay (17.12.2015)
<http://www.vtt.fi/medialle/uutiset/ainutlaatuinen-tuotantokoe-käynnissä-poistopuuvillasta-uutta-kuitua-muotiteollisuudelle>
- When new partners joined in (12.5.2016)
<http://www.vtt.fi/medialle/uutiset/vtt-n-poistopuuvillan-kuiduttamiskokeet-toteutetaan-kesällä>
- About Sustainia 100 Award (7.6.2016)
<http://www.vtt.fi/medialle/uutiset/suomalainen-suljetun-kierron-tekstiilihanke-nousi-sustainia100-listalle>
- When first prototypes were released and piloting at Bioruukki was starting (19.9.2017)
<http://www.vtt.fi/medialle/uutiset/vtt-n-uusiokuidusta-valmistettu-neulos-on-tuntumaltaan-puuvillan-ja-viskoosin-välillä>
- About use of fibres in Independence Day Reception (4.12.2017)
<http://www.vtt.fi/medialle/uutiset/sirpa-pietikäisen-yllä-linnan-juhlissa-anna-ruohosen-suunnittelema-ainutlaatuinen-uusiokuidusta-valmistettu-juhlapuku>

Events. Our project and technology was presented in large events, for example, in SLUSH, Helsinki 11.-13.11.2015, and ITMA textile machinery fair in Fiera Milan 12.-19.11.2015, as well as many smaller events and occasions. Seppälä's textile collection campaign in stores 2015-2016, for example, promoted the project and obtained lot of attention in national press.

Awards. We submitted our case to Circulars 2016 competition and it obtained 'high commendation' and was included into the Circulars Yearbook (Circulars, 2016). Sustainia selected our initiative to their Sustainia 100 listing in 2016 (Sustainia, 2016) (Figure 17).



Figure 17 The Relooping fashion was given highly commended status in Circulars 2016 awards, and it was mentioned in Sustainia 100 listing also in 2016

Networking. Our project also networked with other actors in textile recycling in Finland. We built an interest group which had meeting 12.10.2015, they obtained Relooping news – newsletter, were invited to seminar held in September 2016.

We also networked with Textile 2.0 project and Turku AMK: three project group members, Ali Harlin, Pia Engström and Christian Hindersson attended their study trip to Germany. SUEZ was involved in Textile 2.0 and participated trial of automated sorting of textiles. Co-operation with Textile 2.0 lead to starting of preparation of Telaketju project.

Furthermore project group members Pirjo Heikkilä (VTT), Christian Hindersson and Tiila Korhonen (SUEZ) attended to study trip to Germany and Netherlands organized by STJM (similar to one organized by Textile 2.0) in Autumn 2016, and thus networked with more members of Finnish textile industry interested in textile recycling.

6.2 Related Projects and Continuation of Work

In order to get circular textile business ecosystem to Finland, more activities are needed – missing pieces of the ecosystem has to be built, new business models developed and demand for recycled materials increased.

During the TEKI project VTT carried out Tekes-funded RepoTex project (12/2015 – 12/2016) aiming for commercialization of CCA process. Most feasible commercialisation route was a new technology company. The Infinited Fibre Company (IFC, <http://infinitedfiber.com/>) was founded and transfer of VTT IPR to it is under way. New company will develop technology further, and hopefully build next stage production site to Finland.

Preparation of Telaketju project³ was started as co-operation of TEKI and Textile 2.0 (Turku AMK, 2016) projects. Telaketju targets better utilization of textile waste in Finland by launching simultaneously actions and R&D projects in textile collection and sorting as well as processing and product development. We are building a new kind of multi-stakeholder business ecosystem around textile recycling, and preparing this ecosystem and society for the circular economy transformation in the fields of textiles.

Funding was applied from Ministry of Environment for research organizations, charities, municipal actor, and recycling centres (such as HMARC from TEKI consortium). Tekes funding was obtained to research organizations and companies, such as Touchpoint, Remeo and Pure Waste Textiles from TEKI consortium, and also IFC with CCA technology development activities is involved.

TEKI wet-spinning piloting trials were not successful in Valkeakoski, but finally the piloting was carried out in co-operation with TeKiDe¹ project.

During TEKI project VTT participated Nordic project aiming for stimulating demand for recycled textiles (Watson *et al.*, 2017a). One major task of the project was to collecting case wallet of Nordic companies within circular business. Touchpoint and Pure Waste Textiles were selected to represent Finland in that case wallet (Watson *et al.*, 2017b).

VTT is also involved in proposal preparation for H2020 calls and tries to open possibilities for Finnish industry to be involved in international projects. Many of TEKI company partners have been involved in these applications, as well as build their own research co-operation and networks nationally and internationally.

7. Summary and Conclusions

Circular Economy of Textiles (TEKI) -project aimed for pilot and model the closed circular ecosystem for textiles, where there would be business opportunities and shared value for all parties within value network. Research work carried out in TEKI project can be divided into three themes: 1) piloting and technology, 2) business ecosystem modelling, and 3) consumer attitudes and communication.

Piloting and technology. Target of the piloting was to demonstrate closed loop recycling of post-consumer cotton textiles in pilot scale. Technology was chemical dissolution route using cellulose carbamate chemistry. Cotton raw material was sorted from the discarded textiles coming from consumers. Fabrics were grinded before chemical treatments including carbamatization and dissolution. Spinning dope was filtered before spinning and wet-spun into cellulose carbamate fibres. Fibres were spun into yarns, knitted and also sewed into garments. Protos obtained in lab scale CCA spinning trials included yarns, knitted fabrics and gloves composing 100 % of CCA fibres and protos obtained from pilot scale spinning trials included yarns, fabrics and gala dress obtained from mixture of CCA fibres and mechanically recycled fibres. Original planned closed-loop recycling pilot would have been included also retail and e-sales delivery within reusable packaging, but that part of the pilot did not realized within this project.

Piloting of the chemical recycling proved to be challenging, but we were able to produce fibres first in lab scale and with extended project duration also in pilot scale by the wet spinning technique using the same machinery as in viscose fibre production. Appearance and feel of the fibres were between properties of viscose and cotton fibres. Fibres and knitwear draped nicely and had subtle shine. Strength of the obtained fibres were slightly lower than strength of commercial viscose, but they fibres could be spun into yarns and are, thus, suitable for similar applications as staple viscose fibres. Pilot of the TEKI project facilitated also by RepoTex project have had a role in advancing commercialization of VTT's cellulose carbamate technology. These led to founding of VTT spin-off company - Infinited Fibre Company (IFC) and transferring VTT IPR related to CCA technology to it.

Estimated production costs of these fibres at this point would require slightly higher selling price than that of viscose or cotton, however, better economics can be expected if fibres are well-branded, regulation starts to favour use of recycled materials, and/or price of virgin cotton will rise. When we compared environmental impact of recycled CCA to viscose and cotton we noticed carbon footprint of CCA was approximately 2/3 that of cotton and similar to BAT viscose (best available technology). Water foot print of CCA was 95 % better than cotton. No poisonous chemicals are required unlike viscose since CCA process uses urea instead CS₂ to make cellulose soluble.

Cotton comprises approximately one third of used textile fibres in Finland at the moment, but in addition to 100 % cotton products it is also often used as mixtures. There are currently various methods for separation of polyester-cotton blends, even though these processes are not commercially available yet, R&D work is going on.

Business ecosystem modelling. Transition to a circular economy is a systems-level change and requires a new kind of value creation mind-set. Designing out waste and maintaining the value of products and materials as high as possible for a maximum period of time, requires close collaboration among the whole value network. That is why business ecosystems are at the heart of the transition to a circular economy. Circular business ecosystems are business ecosystems, which together create products, solutions and services based on circular economy principles, and apply circular business models in their way of operating and doing business.

In general one of the biggest issues to solve for a circular business ecosystem for textiles, is the collection and sorting of textiles, especially those no longer suitable for reuse. Therefore, also piloted chemical recycling is not commercially viable yet. In collection similar approaches for separate collection as is now available for paper, board, and plastic packaging materials could be established for textiles, and technologies for automated sorting are under development and should be available soon. Industrial processing of post-consumer also requires removal of parts such as buttons and zippers, and refining of the fabrics according to the use specifications. These lines are already in use in small mechanical recycling plants, but upscaling should be too big challenge. Mechanical, fibre-level recycling is already used around the world even though these volumes could be larger. Thermal recycling is applied commercially in small scale for synthetics, but the chemical process for cotton from cellulose is a widely studied emerging technology.

One outcome of the work started in TEKI project was preparation of activities to complete the value network – preparation and launching of Telaketju value chain projects. Initial work was carried out with Textile 2.0 project. Telaketju composes of project funded by ministry of Environment as R&D projects of research institutes and companies funded by Tekes.

Consumer attitudes and communication. The growing interest among the textile industry, and more specifically the biggest consumer clothing producers and brands, towards recycled textiles, is the key driver for developing new recycling technologies. This places the brands and retailers, who are close to consumers, in a central role in the circular business ecosystem of textiles.

Consumers really like the idea of recycling textile waste to produce new clothes and their attitude towards circular clothing is even more positive than towards second hand clothing. Communication has a remarkable role in convincing consumers of the importance of sustainable consumption: more information about the environmental and ethical aspects of the textile manufacturers and brand owners should be available and communication should be more visible. Consumers expected neutral and fact based information, even humoristic, but preferred to avoid drama in the communication. Transparency of the production process is crucial to gain consumers' trust.

TEKI project has achieved increased public awareness in Finland towards circular economy of textiles and recycling of textile raw materials.

Main outcomes of the project were: 1) successful industrial scale pilot taking VTT's cellulose carbamate technology as chemical recycling route for cotton materials into commercialization bath; 2) gaining better understanding of missing pieces of circular business ecosystem for textiles and launching activities to fill in the value network; and 3) increased consumer awareness through better understanding on consumer communication, which can increase the awareness about possibilities and need for textile recycling in society in general.

References

- Asikainen S., Harlin A., Määttä M., Sivonen E., Valta K. (2012) Method of producing dissolving pulp, dissolving pulp and use of method, EP2895653 (A1), WO2014041251A1, FI20125953
- Asikainen S., Määttä M., Valta K., Sivonen E., Särkilahti A., Kangas P., Harlin A. (2013) From recycled fibers to textile fibers, 23rd IFATCC Congress, 8 - 10 May 2013, Budapest, Hungary, 11 p.
- Becker E. (2016) shared value creation in circular business model: case relooping fashion initiative, Master's thesis, LUT 2017, Available: https://www.doria.fi/bitstream/handle/10024/130791/Master%27s%20Thesis_Essi%20Becker.pdf?sequence=2
- Circulars (2016) The Circular Yearbook 2016 Available: https://thecirculars.org/content/resources/The_Circulars_Yearbook_2016_Final.pdf
- Dahlbo H., Aalto K., Salmenperä H., Eskelinen H., Pennanen J., Sippola K., Huopalahti M. (2015) Tekstiilien uudelleenkäytön ja tekstiilijätteen kierrätyksen tehostaminen Suomessa, Suomen ympäristö 4 | 2015, Available https://helda.helsinki.fi/bitstream/handle/10138/155612/SY_4_2015.pdf?sequence=4
- Ellen MacArthur Foundation (2017) A New Textiles Economy: Redesigning Fashion's Future, 150 p., Available: https://www.ellenmacarthurfoundation.org/assets/downloads/publications/A-New-Textiles-Economy_Full-Report.pdf
- European Commission (2017) Review of Waste Policy and Legislation, Available http://ec.europa.eu/environment/waste/target_review.htm Accessed 23.4.2018
- Fontell P., Heikkilä P. (2017) Model of circular business ecosystem for textiles, VTT Technology 313, available at: <http://www.vtt.fi/inf/pdf/technology/2017/T313.pdf>
- Harlin A. (2017) Technology summary presented to TEK1 project group within WP4 workshop held after 12th TEK1 steering group meeting 3.4.2017
- Heikkilä P., Jetsu P., Kinnunen K., Määttä M., Valta K., Harlin A. (2013) Sustainable nonwoven materials by foam forming using cellulosic fibres and recycled materials, 7th Aachen-Dresden International Textile Conference. Aachen, 28 - 29 Nov. 2013.
- Katajainen L. (2016) Puuvillapohjaisen selluloosakarvamaatin elinkaaritase, Pro gradu thesis, University of Jyväskylä
- Kelheim Fibres GmbH (2017) Brand and Applications. Available http://www.kelheim-fibres.com/produkte/marken_anwendungen_uk.php Accessed 30.10.2017
- Negulescu I.I., Kwon H., Collier B.J., Collier J.R., Pendse A. (1998) Recycling cotton from cotton/polyester fabrics. *Textile Chemist and Colorist* **30**(6), 31–35
- Niinimäki K. (2017) Fashion in a Circular Economy, in Sustainability in Fashion: A cradle to upcycle approach (ed by Henninger C.E. et al.), Springer: Heidelberg, pp. 151-170.
- Palm D., Elander M., Watson D., Kiørboe N., Salmenperä H., Dahlbo H., Moliis K., Kari-Anne Lyng K.A., Clara Valente C., Stefán Gíslason S., Haben Tekie H., Rydberg T. (2014) Towards a Nordic textile strategy. Collection, sorting, reuse and recycling of textiles. *TemaNord* 2014:538, 142 p.
- Resyntex (2017) Project description, Available <http://www.resyntex.eu/the-project> Accessed 24.7.2017
- Shen L., Patel K. (2010) Life cycle assessment of man made cellulose fibres, *Lenzing Berichte* **8** 81–59
- SITRA (2015) Service-based business models & circular strategies for textiles, 66 p. Available <https://www.slideshare.net/SitraEkologia/servicebased-business-models-circular-strategies-for-textiles>
- Sivonen E., Valta K. (2005) Method for preparing a cellulose carbamate solution, FI 20055619, US2009283717 (A1)
- Sustainia (2016) Sustainia 100. A guide to 100 sustainable solutions Available https://issuu.com/sustainia/docs/sustainia100_2016

The Fiber Year (2017) The Fiber Year 2017, Available <https://www.thefiberyear.com/> Accessed 18.4.2018

Teijin (2017) Ecocircle Fibres, Available <http://www2.teijin-frontier.com/english/sozai/specifcs/ecopet-plus.html> Accessed 24.7.2017

Trash-2-Cash (2017) New fibres from pre-consumer and post-consumer waste, Available <https://www.trash2cashproject.eu/trash-2-cash-about-page/> Accessed 24.7.2017

Turku AMK (2016) Textile 2.0 – In English, Available <http://poistotekstiili.turkuamk.fi/in-english/> Accessed 18.4.2018

Valta K., Sivonen E. (2002) Manufacture of cellulose carbamate used as alkaline solution in, e.g. manufacture of fibers and films, by reacting cellulose and urea in mixture containing cellulose, liquid, auxiliary agent and urea, and having specified liquid content, FI20020163 (A)

Valtioneuvosto (2017) Biotalous ja puhtaat ratkaisut, Available <http://valtioneuvosto.fi/hallitusohjelman-toteutus/biotalous> Accessed 18.4.2018

Vehmas K., Raudaskoski A., Heikkilä P., Harlin A., Mensonen A. (2018) Journal of Fashion Marketing and Management, <https://doi.org/10.1108/JFMM-08-2017-0079>

Vehmas K., Ervasti M., Tihinen M., Mensonen A. (2015) Digitalization Boosting Novel Digital Services for Consumers, *ACSIJ Advances in Computer Science: an International Journal* 4(4/16), 80-92

Watson D., Elander M., Gylling A., Andersson T., Heikkilä P. (2017a) Stimulating Textile-to-Textile Recycling, Nordic Council of Ministers, TemaNord 2017:569

Watson D., Gylling A.C., Andersson T., Elander M., Heikkilä P. (2017b) Textile-To-Textile Recycling: Ten Nordic brands that are leading the way, Nordic Council of Ministers, ANP 2017:753

Xu Y., Chen Y., Burman R., Zhao H. (2014) Second-hand clothing consumption: a cross-cultural comparison between American and Chinese young consumers, *International Journal of Consumer Studies* 38, 670–677

Zamani B. (2011) Carbon footprint and energy use of textile recycling techniques. Case study: Sweden. Master of Science Thesis. Chalmers University of Technology, Göteborg, Sweden